On the Possibility of Observing Dark Matter via the Gyromagnetic Faraday Effect

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Context

Dark matter is observed through its gravitational interactions, but to know its nature we probe it with other (i.e., electromagnetic, weak) interactions.

E.g., we constrain DM through its putative annihilation to γ, e^+, ν, ... channels.

But we cannot really answer, "How dark is 'dark'?"

[with thanks to Sigurdson et al., PRD 70, 083501 (2004).]

Suppose a dark matter particle, though electrically neutral, has a non-zero magnetic moment.
How can one test this specific idea?

$\Longrightarrow$ Enter the gyromagnetic Faraday effect.

Outline

- What is the gyromagnetic Faraday effect?

  First review "usual" Faraday effect in the ISM.
- What limits on μ already exist?
- How can one study the gyromagnetic Faraday effect?

  Can be studied through the polarization of the CMB radiation.

  Can also be studied in a terrestrial PVLAS-*like* experiment.
- How stringent are the attainable constraints?

The (Gyroelectric) Faraday Effect

A medium with free charges becomes *circularly birefringent* if $|\mathbf{H_0}| \neq 0$.

Linearly polarized light propagating in the direction of $\mathbf{H_0}$ suffers a rotation

$$\phi = -\frac{e^3}{2c\omega^2\epsilon_0 m^2}\int_0^l dz\, n_e(z) H_0(z)$$

and a time delay

$$\tau_{\rm delay} = \tau(\omega) - \lim_{\omega\to\infty}\tau(\omega) = \frac{e^2}{2c\omega^2\epsilon_0 m}\int_0^l dz\, n_e(z)$$

Studies of the ϕ and $\tau_{\rm delay}$ using radio pulsar sources

[A. G. Lyne and F. G. Smith, Nature **218**, 124 (1968).]

yield n_e and H_0 averaged along the line of sight in the warm ISM.

N.B. ω dependence makes knowledge of the source polarization unnecessary.

Modern surveys map the galactic magnetic field. [e.g., Han et al, ApJ 642 (2006) 868.]

Magnetic field strengths are of few μG scale.

The Gyromagnetic Faraday Effect

A medium with free magnetic moments becomes *circularly birefringent* if $|\mathbf{H_0}| \neq 0$. [D. Polder, Phil. Mag. **40**, 99 (1949).]

The magnetization induced by H_0 (for a spin-1/2 system) is

$$M_0 = n_e \mu \tanh\left(\frac{\mu H_0}{k_B T}\right) \approx n_e \left(\frac{\mu^2 H_0}{k_B T}\right) \text{ with } \mu H \ll k_B T$$

Here

$$\tau_{\rm delay} = \frac{\mu^2 \gamma^2}{2c\,\omega^2 k_B} \int_0^l dz \frac{n_e(z) H_0^2(z)}{T(z)}$$

with $\gamma = g\mu/\hbar$ and $\phi = \phi_0 + \phi_\omega$

$$\phi_0 = \frac{\mu^2\gamma}{2ck_B} \int_0^l dz \frac{n_e(z) H_0(z)}{T(z)} \quad ; \quad \phi_\omega = \frac{\mu^2\gamma^3}{2c\omega^2 k_B} \int_0^l dz \frac{n_e(z) H_0^3(z)}{T(z)}$$

Only ϕ_0 important; with $T = T(z)$

$$\phi_0 = \frac{\mu^2\gamma}{2ck_B T} \int_0^l dz\, n_e(z) H_0(z)$$

The Gyromagnetic Faraday Effect

For **electrons**

$$\tilde{\chi} \equiv \frac{\gamma \mu^2}{k_B T} =\sim 1.5 \cdot 10^{-7} \left[\frac{300\,\mathrm{K}}{T}\right] \frac{\mathrm{cm}^3}{\mathrm{G\,s}}$$

cf.

$$\chi \equiv \frac{e^3}{\omega^2 \epsilon_0 m^2} \sim 1.6 \cdot 10^{-6} \left[\frac{\lambda}{1\,\mathrm{cm}}\right]^2 \frac{\mathrm{cm}^3}{\mathrm{G\,s}} \,,$$

The relative size of the two effects depends on wavelength and temperature.
In the warm ISM, $T \sim 5000^\circ$ K, with $\lambda = 6 - 20$ cm, the magnetic Faraday effect is negligible.
The magnetic Faraday effect can be much larger for dark matter.

- It is denser, and "clumpiness" helps.
- It can accrue over longer distances.
- For $v \sim 200$ km/s, an $\mathcal{O}(1\mathrm{MeV})$ mass DM candidate has $T \sim 2000^\circ$ K. A 100GeV mass candidate has $T \sim 2 \cdot 10^{8\circ}$ K.

  Lighter candidate masses give larger rotations for fixed μ.

We shall consider $\mathcal{O}(\mathrm{MeV})$ DM candidates henceforth.

[C. Boehm et al., PRL 92, 101301 (2004)]

Existing Constraints on μ

Sigurdson et al. analyze constraints on the electric dipole moment and magnetic dipole moment of a DM particle.

[Sigurdson et al., PRD 70, 083501 (2004); PRD 73, 089903 (E) (2006).]

For a DM particle of mass $\mathcal{O}(1\text{GeV})$ or less, their best limit comes from precision electroweak constraints:

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{(1 - M_W^2/M_Z^2)(1 - \Delta r)}$$

$$\Delta r^{\text{SM}} = 0.0355 \pm 0.0019 \pm 0.0002 \quad ; \quad \Delta r^{\text{exp}} = 0.0326 \pm 0.0023$$

$$\Delta r^{\text{new}} < 0.003 \quad \text{at} \quad 95\%\text{CL}$$

Now [Profumo and Sigurdson, astro-ph/0611129]

$$\mathcal{L}_{\text{eff}} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}\frac{a + b\gamma_5}{\tilde{M}}\chi F^{\mu\nu}$$

yields via $\Pi^{\mu\nu}(q^2)$

$$\Delta r \simeq \frac{M_Z^2}{3\pi^2 M^2} \quad \text{with} \quad M^2 \equiv \frac{\pi\tilde{M}^2}{|a|^2 + |b|^2}$$

Existing Constraints on μ

Thus

$$\Delta r^{\rm new} < 0.003$$

yields

$$M \gtrsim 3.4 M_Z \Longrightarrow \frac{a}{\tilde{M}} < 6 \cdot 10^{-6} \mu_B$$

This constraint can be evaded! Enter the **neutron**. (PDG 2006)

$$\mu = -1.9130427 \pm 0.0000005 \mu_N \approx 1 \cdot 10^{-3} \mu_B$$

Using compositeness, the precision ew constraint is modified to

$$\Delta r \simeq \frac{M_Z^2}{3\pi^2 M^2} \left(\frac{1}{1 - M_Z^2/M_C^2} \right)^4 < 0.003$$

M_C need not be $\mathcal{O}(1\text{GeV})$.
If $M_C \sim 10\text{GeV}$, e.g., then the bound is relaxed to $a/\tilde{M} < 4 \cdot 10^{-2} \mu_B$.

Magnetic Faraday Effect on CMB Polarization

To realize a constraint on the EDM or MDM of a DM particle, we must use a photon source of known polarization.

Thus we turn to the polarization of the CMB.

The magnetic Faraday effect from DM acts as a "foreground" source of B-mode polarization.

It is distinguishable from gravitational lensing, e.g., as it cannot impact the temperature correlations.

Let's first see how large the effect can be.

Writing $\gamma = \mu_B g/\hbar$ and $\mu = \mu_B g/2$, we have

$$\phi_0 = \frac{2.54\mathrm{cm}^3}{\mu\mathrm{G\,Mpc}} \left(\frac{\mu}{\mu_B}\right)^3 \left(\frac{m_e}{m_{\rm DM}}\right)^2 n_{\rm DM}(\mathrm{cm}^{-3}) H_0(\mu\mathrm{G}) l(\mathrm{Mpc})\xi$$

ξ is "just" a clumpiness factor.

Using $H \sim 1\,\mu$G, $l \sim 13\,$Gyr $\sim 4000\,$Mpc, $n_{\rm DM} \sim 600\,\mathrm{cm}^{-3}$, $\xi = 0.02$, and with a measurement of $\mathcal{O}(10^{-2}\,\mathrm{rad})$, one finds

$$\mu/\mu_B \sim 1.2 \cdot 10^{-2}$$

This effect is discoverable.

Terrestrial Studies

Terrestrial studies are also possible and possibly yield better control on DM couplings.

- We can apply a strong magnetic field of known strength.
- Measurements of very small rotation angles are possible.
- Faraday rotation accrues coherently under momentum reversal.
- Vacuum pumps do not “pump” dark matter!

Enter the PVLAS experiment. Measure the polarization parameters of laser light after travel through vacuum in a magnetic field. [E. Zavattini et al., PRL 96, 110406 (2006)]
The proposed experiment differs crucially from the PVLAS experiment in that the applied magnetic field must be parallel and not perpendicular to the light.
Use PVLAS parameters. $l_{\rm eff} \sim 4.4 \cdot 10^6$ cm, $H_0 = 5\,\mathrm{T} = 5 \cdot 10^{10}\,\mu$G, $\phi_0 \sim 1 \cdot 10^{-7}$ rad. With $\xi = 1$, get $\mu/\mu_B \sim 0.09$ for a candidate mass of MeV-scale.
Note uncertainty principle limits polarization measurement; one can do better.

[D. Budker, priv. comm.]

Summary and Outlook

We have considered the possibility of observing a DM candidate particle with a non-zero anomalous magnetic moment through the gyromagnetic Faraday effect.

The effect can serve to generate an appreciable source of CMB B-mode polarization and can be studied terrestrially as well.